

# Improving Sustainability of the Corn-Ethanol Industry

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## 12.1 Introduction

Two criteria based on characteristics of plant growth establish when bio-fuels can provide sustainable energy for society. The first criteria: enough solar energy stored during plant growth becomes available for man's use. Pimentel's early evaluation of the US ethanol industry calculated the ratio of BTUs in ethanol: BTUs from fossil energy of corn and ethanol production at less than one. He concluded that ethanol is not sustainable energy, and questioned the industry's existence. Recent energy balance ratios that include adjustments for co-product feed and higher energy efficiency in corn/ethanol production suggest a moderate contribution from captured solar energy. The ratio is around 1.3 (Shapouri et al., 2002). Dale questions the relevance of the net energy criteria, noting that economic value creation is consistent with energy ratios less than or near one. Dale (2007) proposes a second criteria for a sustainable fuel: enough CO<sub>2</sub> in the atmosphere is converted to carbon in the plant and O<sub>2</sub> in the atmosphere through photosynthesis and plant growth to improve global-warming. Comparing greenhouse gas emissions from a refinery and an ethanol plant, some have calculated that emissions could be about 20 % lower with today's corn-ethanol instead of the corresponding output of petroleum-based gasoline (Wang

et al., 1999). Thus, recent calculations of energy ratios and CO<sub>2</sub> emission comparisons both suggest that the corn-ethanol industry is sustainable. Further, public policies to ensure the corn-ethanol industry's existence find moderate justification from both sustainability measures.

Analysis of corn-ethanol should now focus on incremental changes that could occur in the market economy and also improve sustainability. For instance, biomass power is economically competitive and potentially more sustainable than fossil energy inputs (Gallagher et al., 2006). We look at three possibilities for replacing fossil fuel processing energy with biomass: corn stover, willow, and distillers' grains. We also calculate energy ratio improvements. In our CO<sub>2</sub> analysis, we also take a broad view of the ethanol industry as joint producer of fuel and livestock feed in a market context. We show that using biomass power for processing energy, instead of coal and/or natural gas, can improve the sustainability of the corn-ethanol industry substantially. However, the best form of biomass power depends on the nature of the corn supply and demand adjustments that underlie ethanol production.

## 12.2 Energy Balance

A reduction in fossil energy inputs generally improves the energy balance ratio of biofuel output over external fuel inputs. Numerous energy efficiency improvements on the farm and in the ethanol plant have contributed to an increasingly favorable energy balance ratio for corn-ethanol. In the corn processing industry, dry mills typically use a combination of natural gas and market purchases of (coal-based) electricity. But energy balance ratios for sugar-ethanol are much higher, because crop residues are used for processing energy (Gallagher et al., 2006). Conceivably, energy balance could improve with a shift to biomass power.

Table 12.1 compares energy balance situation for a baseline fossil-fuel power and several alternative approaches to biomass power. In the first column, ethanol conversion energy reflects the heat content required for natural gas-based process heat (Shapouri et al., 2002, p. 9, Table 6). Also, market purchases of electricity are calculated from processing electricity requirements, an assumed 30 % efficiency for electrical power production, and the BTU content of the required coal. Three biomass power situations are shown in the next three columns: corn stover, willow, and distillers' grains. All of these biomass alternatives replace the natural gas and coal energy.

But the energy input investment for each biomass power source is unique.

For the willow input, the external energy input is the fuel for planting and maintaining the willow crop, including the energy embodied in machinery depreciation. Also, the energy expended in fertilizer production, distribution, and application is included. We use the estimates provided by Heller et al. (2003). Also, we have calculated the annual average energy use over the 23 year life of a willow plantation. A comparison of external processing energy for willow, 1,159BTU/gallon ethanol, and in the baseline, 48,771BTU/gallon, is quite dramatic – the difference is the sunlight energy stored and then used in biomass power generation.

It is the external energy investment in corn, already included in the baseline energy balance calculation, that also yields the other biomass components of corn stover and



**Table 12.1** *Corn ethanol dry mill: energy use and net energy value with conventional and biomass power for processing*

Processing Power Configuration	Btu/gallon			
	Natural gas & purchased electricity	Biomass power: Corn Stover	Biomass power: willow (SRWC)	Distillers' grain for power
Corn production	21803	21803	21803	21803
Corn transport	2284	2284	2284	2284
Ethanol conversion	48771 <sup>1</sup>	16872	11593	0 <sup>5</sup>
Ethanol distribution	1588	1588	1588	1588
Total energy used	74446	27362	26834.3	25675
By-product Credit	13115 <sup>4</sup>	13115	13115	0
Energy used, net of byproduct credit	61331	14247	13719	25675
Ethanol energy produced	84530	84530	84530	84530
Energy ratio, w/o byproduct credit	1.14	3.09	3.15	3.29
Energy ratio, w/ byproduct credit	1.38	5.93	6.16	3.29

<sup>1</sup>electricity: 12671 btu/gal  
power: 36100 btu/gal from coal natural gas Total: 48771  
Source: Gallagher and Shapouri (2006)

Also assumes 1.1 Kw-hr elec per gal eth, 3413 btu elec per Kw-hr elec, and 0.3 btu-elec per btu input

<sup>2</sup>harvest: 241 btu/gal  
Corn Stover harvest energy from GREET model, see Wang  
fertilizer replacement: 1446 btu/gal  
fertilizer replacement requirement from Gallagher, Dikemen, and Shapouri (2003)  
fertilizer energy requirement from GREET model, see Wang.

<sup>3</sup>plant, harvest, etc. 202.9 btu/gal  
fertilizer 956.4 btu/gal  
Plant management energy use from Heller, Keoleian, and Volk (2002).

<sup>4</sup>17.6 % of baseline energy used.

distillers' grains. So neither input requires a crop production energy allocation. For corn stover, however, some fertilizer is required to replace nutrients in residues left in the field. So replacement fertilizer quantities are calculated (Gallagher et al., 2003). Then the energy embodied in the fertilizer, its production and application are calculated using the GREET model (Wang et al., 1999). Similarly, we include an allowance for external energy expended on stover harvest and machinery use. Our estimate for the fertilizer replacement and harvest, 1687 BTU/gallon in column two, is about one-third higher than the case of a willow crop. But it is still several multiples smaller than the baseline case with fossil energy.

Modification of the energy ratio for distillers' grains is straightforward. First, additional energy investment is not required because the distillers' grains are already available at the processing plant, with the external energy investment made in other parts of the corn production/processing account. So we place a 0 in the ethanol conversion entry for column 4. We also place a 0 for the by-product credit, because the distillers' grains are no longer used for a byproduct feed.

Now look at the Energy Ratio calculations for each of the power configurations. First, the baseline of column 1 is taken from a recent study (Shapouri et al., 2002). Here, the energy ratio is 1.38 with the byproduct credit, and 1.14 without byproduct credit. Without even introducing the byproduct credit, all of the biomass power alternatives have energy ratios in the 3.0 to 3.3 range. With the byproduct credit for stover and willow, the energy ratio increases by another multiple, to the 6.0 region. DG power gives a smaller improvement than other biomass alternatives when the byproduct credit is taken into account.

### 12.3 Crop Production and Greenhouse Gas Emissions

Corn has potential for atmospheric CO<sub>2</sub> reductions because it has a rapid photosynthesis reaction. Field crops are sometimes categorized according to whether they have C<sub>3</sub> and C<sub>4</sub> photosynthesis pathways. C<sub>4</sub> plants, which include the major ethanol feedstocks (corn and sugar), have rapid growth but require substantial nitrogen input to sustain plant growth. C<sub>3</sub> plants, which include soybeans, have slower plant growth and require less nitrogen (Fageria et al. 1997, pp. 44–46).

Indeed, corn replaced soybeans for the recent US ethanol expansion. So, begin by estimating and comparing net CO<sub>2</sub> reduction estimates for corn and beans. In Table 12.2, estimate the total biomass on an acre (column 5) using typical crop yields and biomass-grain ratios. Next, calculate the carbon content for each crop component (column 6) – carbon content estimates used composition data, and relative carbon weights for the protein (amino acid), oil (fatty acid), and starch subcomponents (White and Johnson, 2003; Yu, 2002; Kuiken and Lyman, 1948; Gallagher, 1998). Finally, applying the ratio, 3.66 lb CO<sub>2</sub>/lb C, to the product of the carbon content estimate of column 6 and the biomass quantities in column 5, gives the CO<sub>2</sub>/reduction estimate in column 7. This method of calculation of the CO<sub>2</sub> reduction is valid because photosynthesis places carbon in the plant gets there through photosynthesis. This procedure is used elsewhere (Heller et al., 2003, p. 157).

The downside is that plant growth requires fertilizer, which in turn, generates greenhouse gas emissions associated with machinery use and fertilizer application. To estimate the emission increase we again used the GREET model (Wang et al., 2007). We also confirmed

**Table 12.2** Atmospheric CO<sub>2</sub> (equivalent) reductions associated with plant growth and input use for corn and soybeans

(Col. 1) Commodity	(Col. 2) Input	(Col. 3) Crop yield (bu/acre)	(Col. 4) Grain:total biomass ratio	(Col. 5) Biomass quantity (dwt lb/acre)	(Col. 6) Carbon content (ratio)	(Col. 7) CO <sub>2</sub> reduction (lb CO <sub>2</sub> /acre)
Corn	Fertilizer fuel, machinery, other chemicals	142.2	1.000	6728.9	0.459	11304.2
				6728.9	0.499	12289.3
				13457.8		23593.4
					total	-477.6
soybeans	Fertilizer fuel, machinery, other chemicals	28.96	0.978			-629.6
					net	22486.2
				1563.8	0.527	3016.4
				1529.4	0.577	3229.9
				3093.3		6246.3
					total	-92.9
					net	-629.6
						5523.8



that the GREET estimate is about the same as the default IPCC estimate for typical fertilizer application and runoff conditions in North America. In both cases, the input based emissions increases are an order of magnitude smaller than the plant based emission reduction estimates. Consequently, substantial net CO<sub>2</sub> reductions for an acre on both crops are calculated.

Further, the CO<sub>2</sub> removed from the atmosphere is reduced by a factor of 4 when 1 acre of corn replaces 1 acre of soybeans.

There is considerable discussion and some uncertainty about how unused crop residues decompose. There are N<sub>2</sub>O emissions that the IPCC recommend estimating at 1.25 % of the nitrogen content of the crop residues. These emissions are relatively minor; we estimate the CO<sub>2</sub> equivalent emissions at 477.6 lbs/acre for corn and 92.9 lb/acre for soybeans.

Regarding the destination of carbon from decomposing crop residues, some presume that decomposing plant residues remain in the system, increasing carbon content of the soil, and functioning as fertilizer (Heller et al., 2003). Gallagher et al. (2003) review some data suggesting that soil carbon tends to be related to the tillage (conventional vs. no-till) method, but not to the residue practice (silage vs. field decomposition). Also, a recent simulation looks at corn residues following a switch from conventional tillage to no-till farming (Sheehan et al., 2004, p. 126). In this case, leaving the residues appears to increase soil carbon in the transition to a steady state, until about 10 years after the change in tillage practice. But there is a saturation level. Hence, removing crop residues after 10 years of no-till agricultures may not deplete soil carbon.

In subsequent analysis we assume no-till crop planting and residue removal. But residues probably shouldn't be removed prior to the saturation point to ensure sustainable production agriculture. Otherwise, residue burning would return CO<sub>2</sub> to the atmosphere that could have been sequestered in the soil.

## 12.4 CO<sub>2</sub> Adjustment in a Changing Ethanol Industry

The corn-ethanol industry connects a major CO<sub>2</sub> user, corn, to two major CO<sub>2</sub> producers, cars and cows. When ethanol expands, adjustments in several resource and product markets means that CO<sub>2</sub> balance may improve or deteriorate; the result depends on the extent of factor and product market adjustments. As the ethanol sustainability discussions move from existence to improvement issues, it is important to move beyond the conventional system boundaries of life cycle analysis. To illustrate, we consider the incremental CO<sub>2</sub> effects of a one gallon increase in ethanol production for two polar cases. In Table 12.3, corn supply adjusts to provide input for the ethanol industry. In Table 12.4, corn demand adjusts because the corn supply is fixed.

For estimates of the incremental CO<sub>2</sub> account in Table 12.3, land is diverted from soybeans to corn. The CO<sub>2</sub> collection estimates from Table 12.2 are used, but magnitudes are scaled to correspond to a one gallon increase in ethanol supply. Hence, the lost soybean credit (-10.85), at the bottom of the table, is the lost CO<sub>2</sub> collection in soybean production. But the soybean collection estimate is scaled by the amount of soybean land that must be replaced with corn to get one gallon of ethanol. The increase in corn CO<sub>2</sub> collection is also scaled to a one gallon increase in ethanol. Indeed, the corn credit (19.76) is derived from the carbon content of the corn used for one gallon of ethanol, less the distillers' grain

**Table 12.3 Incremental CO<sub>2</sub> equivalent emissions budget for corn-ethanol processing and alternative processing power configurations. corn market assumption: corn land replaces soybean land; new corn is used for ethanol and DG; soybean output reduction reduces cattle feed in pounds CO<sub>2</sub> equivalent/gallon of ethanol, + for emission decrease and - for emission increase**

	Natural gas heat & coal elec. Col. 1	Corn stover heat & elec. Col. 2	Willow heat & elec. Col. 3	Distillers' Grains Col. 4
<b>Fuel replacement:</b>				
corn credit	19.76	19.76	19.76	19.76
ethanol consumption <sup>3</sup>	-14.12	-14.12	-14.12	-14.12
gas consumption foregone <sup>4</sup>	19.63	19.63	19.63	19.63
other production <sup>2</sup>	2.22	2.20	2.20	2.20
net	27.49	27.49	27.47	27.49
<b>Livestock emissions change</b>				
hogs	0	0	0	0
dairy cows	-15.88	-15.88	-15.88	0
DG credit	9.68	9.68	9.68	9.68
net	-6.20	-6.20	-6.20	9.68
<b>Corn fertilizer</b>				
for corn	-1.25	-1.25	-1.25	-1.25
for biomass <sup>1</sup>	0	-0.261	-0.15	0
net	-1.25	-1.51	-1.40	-1.25
<b>Ethanol processing energy:</b>				
stover credit	32.06	32.06	32.06	32.06
willow credit				
stover decomposition	-32.06		32.06	-32.06
natural gas and coal	-8.55		-32.06	
stover combustion		-12.26		
willow combustion			-11.93	
DG combustion				-9.68
net	-8.55	19.80	20.13	-9.68
Lost soybean credit	-10.85	-10.85	-10.85	-10.85
NET GAIN(+) or LOSS(-)	0.64	28.71	29.15	15.37

<sup>1</sup>includes machinery and fuel allowance.

<sup>2</sup>refinery emissions from gasoline production(3.8 lb /gal, CO<sub>2</sub> equi) are replaced by farm diesel, machinery, insecticide, and pesticide emissions (totaling 1.64 lb/gal, CO<sub>2</sub> equi).

<sup>3</sup>calculated using the carbon content of ethyl alcohol (52.2%) and assuming complete combustion.

<sup>4</sup>calculated using the carbon content of gasoline (86.3%) and assuming complete combustion.



**Table 12.4** Incremental CO<sub>2</sub> equivalent emissions budget for corn-ethanol processing and alternative processing power configurations. corn market assumption: hog feeding reduced for all corn supply, and DG feeding to dairy cattle. No change in corn production ... in pounds CO<sub>2</sub> equivalent/gallon of ethanol, + for emission decrease and - for emission increase

	Natural gas heat & coal elec.	Corn stover heat & elec	Willow heat & elec.	Distillers' Grains
<b>Fuel replacement:</b>				
Corn credit	0	0	0	0
ethanol consumption	-14.12	-14.12	-14.12	-14.12
Gas consumption foregone other production <sup>2</sup>	19.63	19.63	19.63	19.63
Net	2.20	2.20	2.20	2.20
<b>Livestock emissions change</b>	7.71	7.71	7.71	7.71
hogs				
dairy cattle	12.21	12.21	12.21	12.21
DG credit	-20.11	-20.11	-20.11	0
net	0	0	0	0
<b>Corn fertilizer</b>	-7.90	-7.90	-7.90	12.21
for corn				
for biomass <sup>1</sup>	-1.25	-1.25	-1.25	-1.25
net	0	-0.26	-0.15	0.00
<b>Ethanol processing energy:</b>	-1.25	-1.51	-1.40	-1.25
stover credit				
willow credit	0	0	0	0
stover decomposition			32.06	
natural gas and coal	0	32.06 <sup>3</sup>	0	0
stover combustion	-8.55			
willow combustion		-12.26		
DG compustion			-11.93	
Net	-8.55	19.80	20.13	-9.68
<b>NET GAIN(+) or LOSS(-)</b>	-9.99	21.10	18.54	8.99

<sup>1</sup>includes machinery and fuel allowance.

<sup>2</sup>refinery emissions from gasoline production(3.8 lb/gal, CO<sub>2</sub> equi) are replaced by farm diesel, machinery, insecticide, and pesticide emissions(totalling 1.64 lb/gal, CO<sub>2</sub> equi).

<sup>3</sup>decomposition forgone by using biomass for power.



byproduct, its carbon and CO<sub>2</sub> collection (9.68). The stover credit of 32.06 is scaled to the 1/2.7 bushels of corn. These same CO<sub>2</sub> collection estimates hold across all columns of Table 12.3, because the same crops are used regardless of the processing power configuration.

CO<sub>2</sub> emissions estimates are presented for the major uses and inputs associated with ethanol processing. The fuel replacement and livestock emissions are the same for all columns. But the input emissions change significantly across power configurations. The net fuel replacement is a gain (27.47). It consists of the CO<sub>2</sub> collection of corn, the ethanol fuel burning in an automobile (-14.12), the gasoline consumption foregone (19.62) and other production (2.20). Other production reflects the net gain from reduced petroleum extraction and processing against the increase in (non-fertilizer) agricultural inputs. The ethanol and gasoline estimates are calculated using the carbon content, in effect assuming an ideal engine that burns everything completely to carbon dioxide and water.

The net emissions estimate for livestock (-6.20) represents a loss. The partial credit from corn production, the carbon embodied in distillers' grains, is a gain (9.68). But the loss associated with emissions from dairy cows (-15.88) is a larger net loss. The dairy cow emission estimate used IPCC default emissions of each major greenhouse gas (carbon dioxide, methane and nitrous oxide) in North America, and conventional weighting procedures for conversion to carbon dioxide equivalents.

The corn fertilizer and ethanol processing emissions vary across columns with processing power alternatives. The fertilizer emissions include the corn crop, and in some cases, the fertilizer for the biomass crop used for ethanol energy.

Differences in emissions across power configurations are important in the net CO<sub>2</sub> position associated with ethanol processing:

1. The main baseline entry (col. 1) for processing emissions (-8.55) reflects the natural gas and coal used. The stover component of corn plant collections (+32.06) is a large credit, but there is a corresponding offset (-32.06) associated with stover decomposition in the atmosphere. So the net processing and the gas/power emissions are the same.
2. When corn stover is the power source (col. 2), the emissions from decomposition are replaced with a stover combustion estimate (-12.26) from GREET. Hence, net position becomes a collection instead of an emission at 19.80.
3. When willow crop is the power source (col. 3), the stover credit and decomposition are both present. Additionally, a willow credit is to account for crop growth. Finally, a woody crop combustion estimate from GREET is used again; the net processing is similar to stover, at 20.13.
4. When distillers grain is used as the power source (col. 4), an emissions estimate based on the carbon content of DGs is used. The net processing change shows as a loss, but conceptually, it offsets the DG credit from the livestock account.

Now look at the net gains and losses for an ethanol expansion at the bottom of Table 12.3. First, the Baseline net emission is a relatively small net gain of 0.62 lbs/gal, which suggests that ethanol does not improve emissions. However the net gains are considerably larger with any of the three forms of biomass power. The stover and willow cases are considerably larger, near 29 lb/gal of CO<sub>2</sub>. The distillers' grain power improves emissions moderately, about 15 lb/gal of CO<sub>2</sub>. The reason for the increase with all forms of biomass



power is that there's an offsetting carbon collection at work with biomass power, whereas there's only an emission with the fossil fuel power in the baseline case.

Notice that the net improvement with an ethanol expansion is neutral for the baseline, even despite a significant net reduction associated with increased livestock feeding.<sup>1</sup> Partly, this occurs because of the positive land production credit for corn. Partly, it occurs because of our idealized perfect engine that converts all C to CO<sub>2</sub>.

Next, consider the incremental CO<sub>2</sub> account of Table 12.4. Here, corn and soybean production is fixed, so the component credits (corn, DG, and stover) are all zero on the margin. Compared with Table 3S then, a level reduction in the CO<sub>2</sub> benefit associated with both product markets occurs. The fuel replacement net benefit is now only 7.71. The livestock net emission is slightly smaller, at -7.90, because reduced emissions from declining hog production and corn feeding, 12.21, replace the DG credit. Next, the soybean credit is excluded from Table 12.4, because there is no change in soybean production. So the baseline net (for col. 1) is -9.99, a substantial loss. Apparently, the CO<sub>2</sub> situation deteriorates when the ethanol industry expands by diverting corn from hog feeding when it increases dairy feeding and uses fossil fuel based power.

However, adoption of any of the biomass power options improves the net CO<sub>2</sub> situation regardless of whether supply or demand adjusts. For instance, the net gain improvement from switching to corn stover power is  $28.71 - 0.64 = 28.07$  in Table 12.3. About the same improvement, 31.09, is obtained from Table 12.4. Further, the relative ranking of the power options is about the same for both market situations.

## 12.5 Conclusions

We looked at some possible changes in corn-ethanol (CE) industry practices that improve sustainability, using contributions to energy balance and global warming as the criteria. Our calculations suggest that moving from fossil fuel to biomass power can change the energy balance fraction from a moderate to a substantial contribution. Similarly adopting biomass power could induce a substantial improvement in the greenhouse gas contribution of the corn ethanol industry. On both the energy balance and global warming scores, all of the biomass power forms considered improved the situation, although some were better than others. Any or some combination of power alternatives could be included in actual implementations, after economic considerations such as production costs, and storage costs are taken into account.

Expanding the CE industry also has the potential to improve the balance of greenhouse gasses. However, there is a need to expand the traditional system boundary and incorporate

<sup>1</sup> Consider the conventional system boundary and refinery/bio-refinery comparison at the baseline. A unit of gasoline would emit:

-19.63 gasoline combustion  
-3.80 refinery/extraction  
-23.43 lb/total

A unit of ethanol would emit:

-14.12 ethanol combustion  
-11.44 corn and ethanol production  
-25.56 subtotal  
+8.91 land credit, corn less soy  
-16.65

Without the land credit, ethanol emits 9.1 % more than gasoline due to higher processing emissions. With the land credit, ethanol emits 29 % less than gasoline. Wang uses a smaller land credit for corn and a smaller combustion advantage for ethanol.



LCA into economic analysis. Then realistic adjustments of agricultural land and livestock markets that accompany CE industry expansion could also be included. Our exploratory calculations suggest that the GHG balance improves when corn supply expands to accommodate increased ethanol processing. Also, the relative efficiency of corn in photosynthesis is an important contributing factor when corn-replacing-soybeans is the dominant supply adjustment. In contrast, the GHG balance deteriorates when corn demand adjusts, because the supply does not make a contribution on the margin; and because increased livestock emissions are significant.

Our exploratory calculations of incremental changes in GHG balance are a useful reference point for evaluating what happens when the CE expands. But the corn industry may need to make substantial improvements before our reference level is realized. For instance, our analysis of residue removal assumed no till farming and a decade-long adjustment period to rebuild soil carbon. Also, the nitrogen analysis assumed that the IPCC reference levels of fertilizer runoff occur. But there may also be potential for improvement far beyond the reference level. Perhaps livestock emissions can be reduced below the IPCC default levels. Alternatively, the CE industry could move to reduce the connection to the livestock industry, by using high starch corn varieties that reduce the proportion of DGs that are produced, or by using the DGs as a source of processing power.

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